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Indian Standard

BASIC METHOD FOR THE MEASUREMENT OF RESONANCE FREQUENCY AND EQUIVALENT SERIES RESISTANCE OF QUARTZ CRYSTAL UNITS BY ZERO PHASE TECHNIQUE IN A π-NETWORK

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Indian Standard

BASIC METHOD FOR THE MEASUREMENT OF RESONANCE FREQUENCY AND EQUIVALENT SERIES RESISTANCE OF QUARTZ CRYSTAL UNITS BY ZERO PHASE TECHNIQUE IN A π-NETWORK

(*Continued on page* 2)

(*Continued from page* 1)

Indian Standard
BASIC METHOD FOR THE MEASUREMENT OF RESONANCE FREQUENCY AND EQUIVALENT SERIES RESISTANCE OF QUARTZ CRYSTAL UNITS BY ZERO PHASE TECHNIQUE IN A π-NETWORK

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 23 January 1976, after the draft finalized by the Piezoelectric Devices for Frequency Control and Selection Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 The object of this standard is to provide basic method for the measurement of resonance frequency and equivalent series resistance of quartz crystal units by zero phase technique in a π-network.

0.3 While preparing this standard, assistance has been derived from IEC Publication 444-1973 'Basic method for the measurement of resonance frequency and equivalent series resistance of quartz crystal units by zero phase technique in a π-network' issued by the International Electrotechnical Commission.

0.4 In reporting the result of a test or analysis made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS : 2-1960*.

1. SCOPE

1.1 This standard specifies a simple method of measurement of resonance frequency and equivalent series resistance of quartz crystal units in the frequency range of 1 MHz to 125 MHz with a fractional frequency accuracy ranging between 10^{-6} and 10^{-8} depending on the type of crystal and an accuracy on the equivalent series resistance of ± 2 percent to ± 5 percent depending on the accuracy of the voltage measurement by a zero phase technique in a π-network.

NOTE — The electrical characteristics of the π-network are fully specified.

*Rules for rounding off numerical values (*revised*).

2. RESONANCE FREQUENCY OF QUARTZ CRYSTAL UNITS

2.1 The resonance frequency is defined as the lower of the two frequencies of the crystal unit alone under specified conditions at which B_{12} is zero. At this frequency, the equivalent series resistance is $1/G_{12}=R_r$.

2.1.1 The crystal unit is a three-terminal network with a complex transfer admittance $Y_{12}=G_{12}+jB_{12}$, as defined in **A-1.1**.

2.1.2 The holder is considered as the common terminal.

2.1.3 For glass holders, the third terminal is defined in **3**.

3. REFERENCE PLANE AND SHIELDING BOX

3.1 Because of lead inductance of the crystal unit, it is necessary for the crystal unit to specify a reference plane at which the measurements are to be made. This plane is located at a distance of 2 mm from the place where the pins or leads emerge from the crystal unit, unless otherwise specified. The third terminal for glass holders is a metal shielding box with internal dimensions of 27 mm height and 40 × 40 mm base plane (base plane= reference plane) and closed at the top. The crystal unit is to be located at the centre of the base plane of the shielding box.

4. PRINCIPLE OF MEASUREMENT

4.1 The measurement is reduced to a 2-terminal impedance measurement by inserting the crystal unit in a π-network (*see* Fig. 1).

4.1.1 The phase of the crystal transfer admittance is indicated on a phase meter connected across the π-network. The frequency giving zero phase reading is measured.

4.1.2 Zero phase is calibrated by inserting a reference resistor in the π-network. The value of the equivalent series resistance can be calculated from the voltage readings on channels *A* and *B*.

5. MEASURING SETUP

5.0 The measuring setup consists basically of a π-network connected with coaxial cables to the associated equipment (*see* Fig. 1).

5.0.1 The fact is emphasized that the construction of the π-network determines the accuracy of the setup, whereas the associated equipment can be extended, if necessary, to produce a very sophisticated setup. For this reason, only the essential elements of the associated equipment are specified (*see* **5.3**).

5.1 *Π*-Network

5.1.1 *Electrical Specification*

5.1.1.1 *Circuit diagram* — A typical circuit diagram is given in Fig. 2.

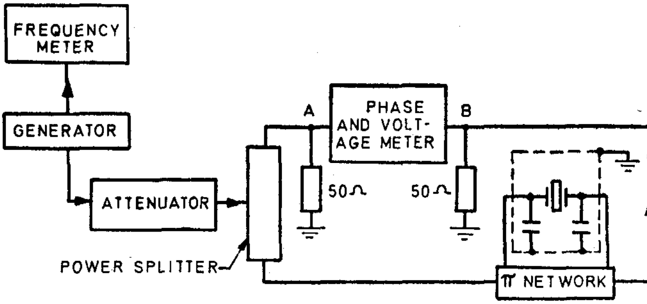
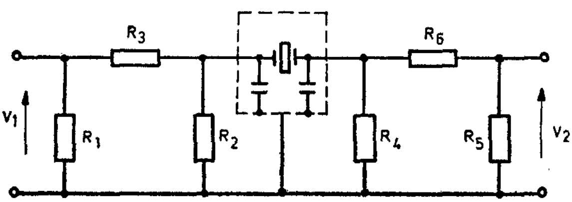


Fig. 1 Basic Measuring Setup



$R_1 = R_5 = 159\ \Omega$ (disk type)
$R_2 = R_4 = 14{\cdot}2\ \Omega$ (disk type)
$R_3 = R_6 = 66{\cdot}2\ \Omega$ (rod type)
Tolerance ± 1 percent

Note — The function of the input and output pads is twofold:

a) to match the crystal impedance to the associated equipment, and
b) to attenuate reflections from the associated equipment.

Fig. 2 Circuit Diagram

5.1.1.2 *Frequency range* — The frequency range shall be 1 to 125 MHz.

5.1.1.3 *Phase requirements* — At all frequencies between 1 MHz and 125 MHz the phase measured at 75 Ω shall not deviate by more than $\pm 0{\cdot}2°$ from the phase measured at 25 Ω (*see* **6.1**).

At a frequency of 125 MHz, the phase over the resistance range of 0 to 100 Ω shall not deviate by more than $\pm 0{\cdot}5°$ from the phase measured at 25 Ω (*see* **6.1** and Fig. 3).

5.1.1.4 At a frequency of 125 MHz, the reflection coefficient measured with the shorting blank, with the dimensions specified in **5.2.2**, shall be

smaller than 2 percent within the reference temperature range —55 to +105°C. The output and input shall be terminated with 50 Ω.

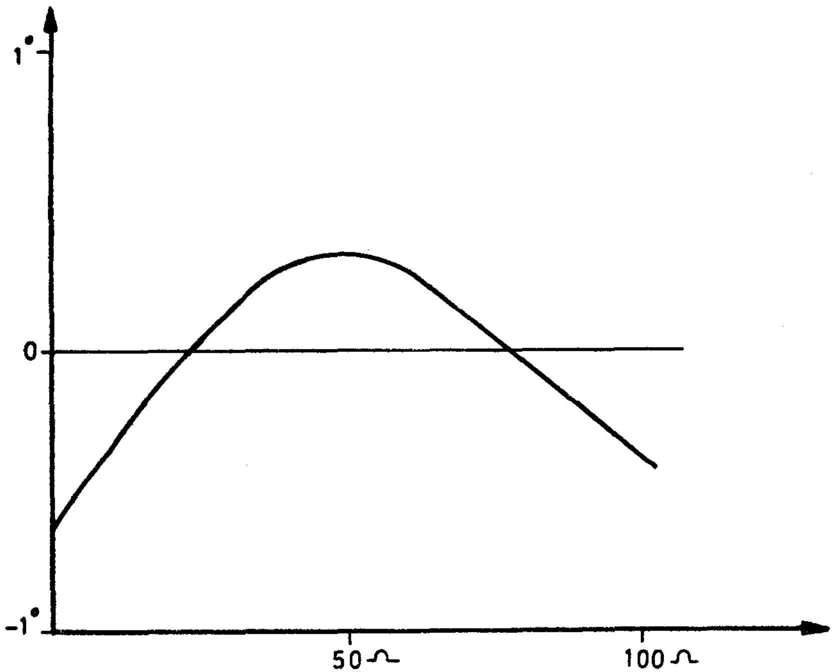


Fig. 3 Typical Phase-Resistance Curve, Measured at 125 MHz

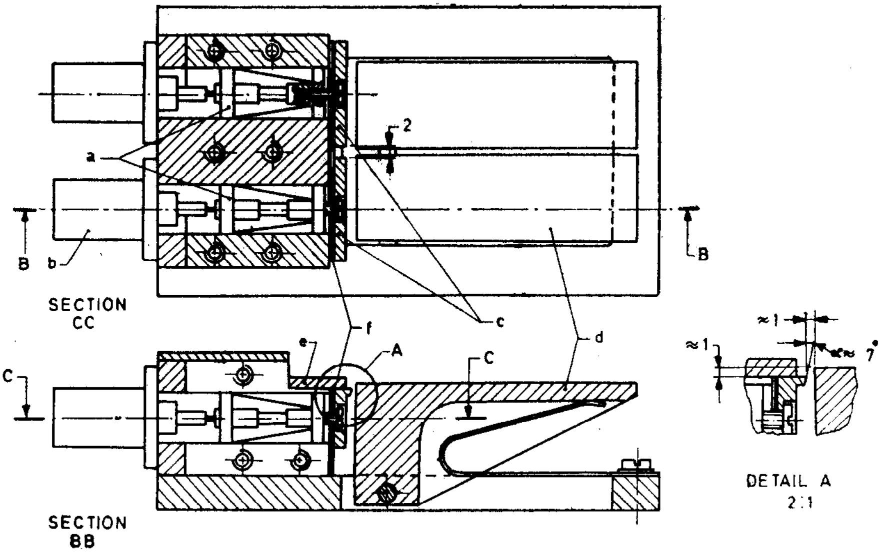
5.1.1.5 Measured with the shorting metal blank of **5.2.2** in the π-network, the transducer attenuation over the specified frequency range shall be 29·6 ± 0·3 dB.

5.1.1.6 The capacitance between contact plates shall be smaller than 1 pF.

5.1.1.7 With the 75 Ω reference resistor (*see* **5.2.1**) in the π-network of the setup of Fig. 1, the phase is measured over the temperature range —55 to +105°C at a frequency of 125 MHz. The permissible difference is 0·2° with reference to the value at +25°C.

5.1.1.8 The resistance between the contact plates and body of the terminated π-network shall be 12·5 Ω. The tolerance is defined by the tolerances of R_1 to R_6 (*see* Fig. 2).

5.1.2 *Mechanical Specification* — A typical π-network which meets the requirements of **5.1.1** is given in Fig. 4.



a = Two resistive attenuators (14·8 dB each) in a metal body, consisting of resistors *R* to R_6 (*see* Fig. 2).

b = Two coaxial connectors (50 Ω) with sufficiently low contact resistance.

c = Two contact plates against which the crystal terminals are pressed. The contacts with the crystal terminals shall be made at the top edges of the contact plates, which serve to define the reference plane.

d = Two spring-loaded plastic blocks.

e = Plastic spacer to determine the location of the reference plane.

= Dielectric.

All dimensions in millimetres.

FIG. 4 CONSTRUCTIONAL PARTS OF TYPICAL *Π*-NETWORK

5.2 Accessories of *Π*-Network

5.2.1 *Reference Resistors*

5.2.1.1 The shape and dimensions of the resistors for the calibration are given in Appendix B.

5.2.1.2 Resistance values for initial calibration are 25 Ω, 50 Ω, 75 Ω and 100 Ω. At 125 MHz the phase of the admittance of the resistors measured in the reference plane shall be less than 0·2°.

The 25 Ω resistor shall also meet this requirement at 90 MHz. For frequency and resistance measurements (*see* **6.2**), the 75 Ω resistors shall meet the above requirements over the whole frequency range.

5.2.2 *Shorting Blank* — The shorting blank is a metal plate with dimensions $12 \times 10 \times 1$ mm.

5.3 Associated Equipment

5.3.1 *Generator*

5.3.1.1 At both sides of the frequency for which the generator is adjusted and within 10 percent of that frequency, the total output power, apart from that at the adjusted frequency, shall be at least 60 dB below the main output.

The level of spurious and harmonics from the generator shall be sufficiently low for the accuracy of the phase meter not to be affected (typical value: —40 dB). The frequency resolution and stability of the generator shall be adequate to enable measurements to be carried out on the highest Q crystal under consideration (typical value better than $1 \cdot 10^{-7}$).

5.3.1.2 The phase noise is measured at resonance frequency in the setup of Fig. 1, with a high Q crystal ($Q > 500\,000$) in the π-network. The indicated phase jitter shall be less than 0·2°.

5.3.1.3 The maximum available output power level shall be at least 24 dB above the nominal crystal drive level.

5.3.1.4 Source impedance is 50 Ω.

5.3.2 *Variable Attenuator* (50 Ω) — A suitable variable attenuator required for drive level adjustment only, may be incorporated in the generator.

5.3.3 *Power Splitter* — A suitable power splitter may be incorporated in the π-network. Its circuit diagram is given in Fig. 5.

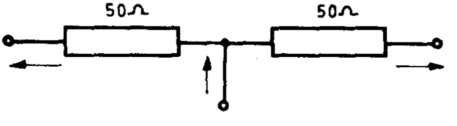


FIG. 5 POWER SPLITTER CIRCUIT DIAGRAM

5.3.4 *Phase and Voltage Meter* — The phase meter serves as an indicator. From the voltmeter reading the equivalent series resistance can be deduced.

Requirements are described in **5.3.4.1** to **5.3.4.4**.

5.3.4.1 Phase error at zero reading as a function of time (zero drift) and as a function of voltage change by a factor of 5 measured at channel B shall be less than 0·2°.

NOTE — Precautions shall be taken that harmonics do not affect the accuracy of the phase reading.

5.3.4.2 The sensitivity on channel B shall be at least 25 dB below the nominal crystal drive level.

5.3.4.3 The reflection coefficients at *A* and *B* channel terminals shall be less than 2 percent. Impedance is 50 Ω.

5.3.4.4 The ratio of voltages on channels *A* and *B* shall be measured with a precision of 2 percent.

5.3.5 *Cables*

5.3.5.1 Double-shielded cables (50 Ω) capable of withstanding the temperature range of -55 to $+105$°C shall be used.

5.3.5.2 The reflection coefficients at the cable terminals shall be less than 5 percent.

5.3.5.3 It is preferable to choose the length of the cables connecting the output of the power splitter to the input of the π-network so that, with a reference resistor of 75 Ω inserted in the π-network, the phase shift between channels *A* and *B* at all frequencies within the range of 1 to 125 MHz is not more than 0·2°.

5.3.6 *Frequency Meter* — The accuracy and stability of the frequency meter shall be better than $1 \cdot 10^{-8}$.

6. METHOD OF MEASUREMENT

6.1 Initial Calibration of Π-Network

6.1.1 The 25 Ω reference resistor (*see* **5.2.1**) shall be inserted in the π-network.

6.1.2 The signal generator shall be adjusted to a frequency of 125 MHz and the output level adjusted to a value well below the maximum permissible power level of the π-network.

6.1.3 The phase meter shall be adjusted to zero reading.

6.1.4 The 25 Ω reference resistor shall be replaced by the 75 Ω reference resistor (*see* **5.2.1**).

6.1.5 The phase reading shall be taken. For phase requirements reference shall be made to **5.1.1.3**.

6.1.6 If the π-network does not fulfil the requirements specified in **6.1.1** to **6.1.5**, the compensation procedure as given in **A-3** should be followed.

NOTE — If the π-network does not fulfil the above requirements, it is an indication that the stray inductances in the network are excessive.

6.1.7 The steps **6.1.1** to **6.1.5** shall be repeated at a frequency of 90 MHz.

6.1.8 The steps **6.1.1** to **6.1.5** shall be repeated with the 25 Ω reference resistor and shall be replaced in step **6.1.4** by 0, 50, 75 and 100 Ω respectively (*see* **5.1.1.3**).

6.1.9 The steps **6.1.1** to **6.1.5** shall be repeated over the temperature range -55 to $+105$°C. For requirements, reference shall be made to **5.1.1.7**.

6.2 Frequency and Resistance Measurement

6.2.1 *Initial Calibration*

6.2.1.1 The shorting blank shall be inserted in the π-network.

6.2.1.2 The signal generator shall be adjusted to nominal frequency $\pm 0 \cdot 1$ percent and the required power level adjusted to 24 dB above the nominal crystal drive level, unless otherwise specified.

NOTE — Further explanation is given in **A-2.1**.

6.2.1.3 The *A* and *B* channel voltage readings, V_{AS} and V_{BS} respectively shall be taken and the value of *K* calculated using the expression:

$$K = \frac{V_{BS}}{V_{AS}}$$

6.2.2 *Measurement*

6.2.2.1 The 75 Ω reference resistor shall be inserted in the π-network.

6.2.2.2 The phase meter shall be adjusted to zero phase reading.

6.2.2.3 The reference resistor shall be replaced by the crystal unit and the metal holder or shield, whichever is applicable, shall be suitably earthed.

6.2.2.4 The frequency shall be adjusted for zero phase reading.

6.2.2.5 The frequency shall then be read.

6.2.2.6 *A* and *B* channel voltage readings, V_{AC} and V_{BC} respectively shall be taken.

6.2.2.7 The equivalent resistance can be calculated from the formula:

$$R_r = 25.\left(K \frac{V_{AC}}{V_{BC}} - 1 \right)$$

APPENDIX A

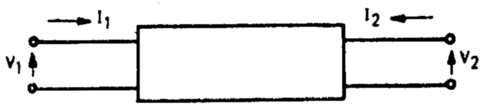
[*Clauses* 2.1.1, 6.1.6 *and* 6.2.1.2 (Note)]

ADDITIONAL INFORMATION ON ACCURACY

A-1. ANALYSIS OF THE MEASUREMENT

A-1.1 A piezoelectric quartz crystal unit can be considered as a 3-terminal network.

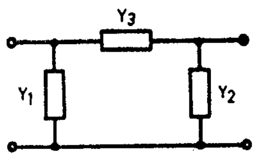
A-1.1.1 In general, a 3-terminal network (*see* Fig. 6) can be described by the admittance matrix :



$I_1 = Y_{11}V_1 + Y_{12}V_2$
$I_2 = Y_{21}V_1 + Y_{22}V_2$
$Y_{12} = Y_{21}$ for a reciprocal network

FIG. 6 3-TERMINAL NETWORK

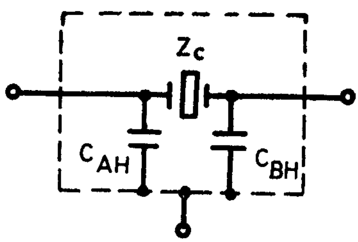
A-1.1.2 If the network is a π (*see* Fig. 7), the matrix is :



$Y_{11} = Y_1 + Y_3$
$Y_{22} = Y_2 + Y_3$
$Y_{12} = Y_{21} = -\ Y_3$ transfer admittance

FIG. 7 Π-NETWORK

A-1.1.3 When applied to a crystal unit, the network shall be as shown in Fig. 8.



$Y_1 = jw\ C_{AH}$
$Y_2 = jw\ C_{BH}$
$Y_3 = 1/Z_c$
Z_c = crystal impedance if $C_{AH} = C_{BH} = 0$

FIG. 8 EQUIVALENT NETWORK OF A CRYSTAL UNIT

A-1.2 *Π*-**Network** — The crystal unit in a π-network is shown in Fig. 9.

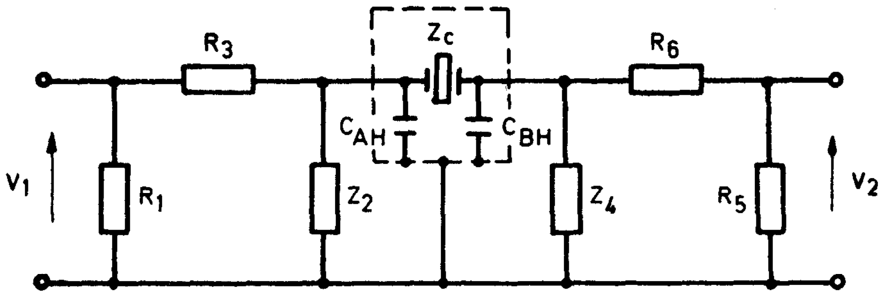


FIG. 9 CRYSTAL UNIT IN A Π-NETWORK

A-1.2.1 The voltage transfer is:

$$\frac{V_2}{V_1}=\frac{R_5}{R_5+R_6}\cdot\frac{1}{R_3\cdot A_2\cdot A_4}\cdot\frac{1}{Z_C+\frac{1}{A_2}+\frac{1}{A_4}}$$

where

$$A_2 = 1/Z_2+1/R_3+j\omega\, C_{AH}, \text{ and}$$
$$A_4 = 1/Z_4+1/(R_5+R_6)+j\omega\, C_{BH}.$$

A-1.2.2 Apparently the crystal unit is loaded with a series impedance, Z_S.

where

$$Z_S = 1/A_2+1/A_4.$$

A-1.2.3 For the purpose of this standard, all the stray reactances have been considered to be lumped in impedances Z_2 and Z_4.

A-2. ACCURACY OF THE MEASUREMENT

A-2.0 Although the setup has been designed to give a very good accuracy, there remain three sources of minor errors as described in **A-2.1** to **A-2.3**.

A-2.1 Variation of Drive Level

A-2.1.1 In general, the resonance frequency and ESR of a crystal unit are dependent on the level of drive. The magnitude of this effect is determined by the crystal unit under test.

A-2.1.2 However, the design of the π-network is such that a change of ESR does not seriously affect the drive level (*see* Fig. 10).

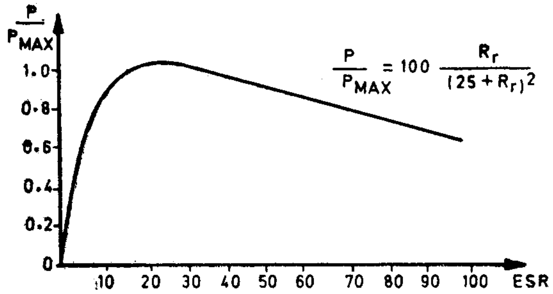


FIG. 10 VARIATION OF DRIVE LEVEL

A-2.1.3 For example, a change of ESR from 9·5 to 65·5 Ω results in a change of power level of 20 percent. In most cases, this is acceptable.

A-2.1.4 For crystals with a very high or very low ESR, the drive level may be adjusted according to Fig. 10, if required.

A-2.2 Phase Shifts

A-2.2.1 In the neighbourhood of resonance frequency, the phase of $Z_c + Z_s$ is given by φ

$$\varphi = \frac{2\,\Delta f}{f} \cdot Q_{eff},$$

where

φ is in radian,

$\Delta f = f - f_r$, and

$$Q_{eff} = \frac{1}{2\pi f_r\,(R_2 + R_4 + R_r)\,C_1}.$$

$$\text{Thus}: \frac{\Delta f}{f} = \frac{\varphi}{2\,Q_{eff}}$$

A-2.2.2 For example, for a crystal of 60 MHz and a $Q_{eff} = 40\,000$,the resulting relative frequency error is $1 \cdot 10^{-7}$ for a residual phase error of 0·45°.

A-2.2.3 The phase errors due to a change of R_r can for all practical purposes be eliminated by replacing the crystal unit by a (nearly ideal) reference resistor (*see* Appendix B) with a resistance approximately equal to R_r.

A-2.3 Stray Holder Capacitances

A-2.3.1 The influence of the stray holder capacitances C_{AH} and C_{BH} on the measurement of resonance frequency is given in **A-2.3.2** to **A-2.3.4**; the holder capacitances are in parallel with Z_2 and Z_4 (*see* Fig. 9).

A-2.3.2 The impedance of the combination Z_2 and C_{AH} is:

$$Z'_2 = \frac{Z_2}{1 + Z_2 j\omega C_{AH}} \text{ and similarly } Z'_4 = \frac{Z_4}{1 + Z_4 j\omega C_{BH}}$$

A-2.3.3 For example, if $f_r = 100$ MHz, $C_{AH} = C_{BH} = 2$pF, $C_1 = 0{\cdot}7$pF and $Z_2 = Z_4 = 12{\cdot}5\ \Omega$,

then: $Z'_2 = Z'_4 = 12{\cdot}5 - 0{\cdot}19\,j$

A-2.3.4 Ignoring the holder capacitances results in a systematic frequency error of:

$$\frac{\Delta f}{f} = 8 \times 10^{-7} \text{ for } Q_{eff} = 20\ 000$$

Hence, the difference will be the same for all π-networks.

A-3. COMPENSATION OF INDUCTANCE OF R_2 AND R_4

A-3.1 In general, the equivalent circuit of a resistor (as Z_2 and Z_4 of Fig. 9) measured at high frequency is given in Fig. 11.

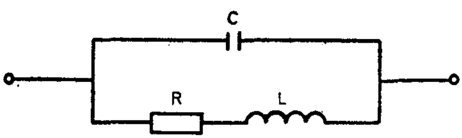


FIG. 11 EQUIVALENT CIRCUIT OF A RESISTOR

A-3.2 The admittance is:

$$A = j\omega C + 1/(R + j\omega L) = \frac{Rj\omega C + 1 - \omega^2 LC}{R + j\omega L}$$

A is resistive if $R^2 C = (1 - \omega^2 LC) L$.

A-3.3 If $\omega^2 LC \ll 1$, then $R^2 = L/C$.

The condition $\omega^2 LC \ll 1$ may then be written as $\omega L \ll R$. The validity of this relation will be checked at a second frequency.

A-3.4 In the present state of the art, it appears that compensation is possible for $R_2 = 14{\cdot}2\ \Omega$ up to 125 MHz.

Hence, if $L \ll R/\omega = 18$ nH, compensation can be accomplished up to 125 MHz.

The compensation is accomplished by varying the thickness of the dielectric layers between contact plates and body.

A-4. MEASUREMENT ERROR OF RESONANCE RESISTANCE

A-4.1 The measurement error of resonance resistance is:

$$\triangle R_r = \left(\frac{\triangle V_{BS}}{V_{BS}} + \frac{\triangle V_{AC}}{V_{AC}} - \frac{\triangle V_{AS}}{V_{AS}} - \frac{\triangle V_{BC}}{V_{BC}}\right) \cdot \frac{V_{AC}}{V_{AS}} \cdot \frac{V_{BS}}{V_{BC}} \cdot 25$$

where

$\triangle V_{AC}$ = error in V_{AC},
$\triangle V_{AS}$ = error in V_{AS},
$\triangle V_{BC}$ = error in V_{BC}, and
$\triangle V_{BS}$ = error in V_{BS}.

APPENDIX B

(*Clauses* 5.2.1.1 *and* A-2.2.3)

SHAPE AND DIMENSIONS OF REFERENCE RESISTORS

B-1. The shape and dimensions of the reference resistors shall be as shown in Fig. 12.

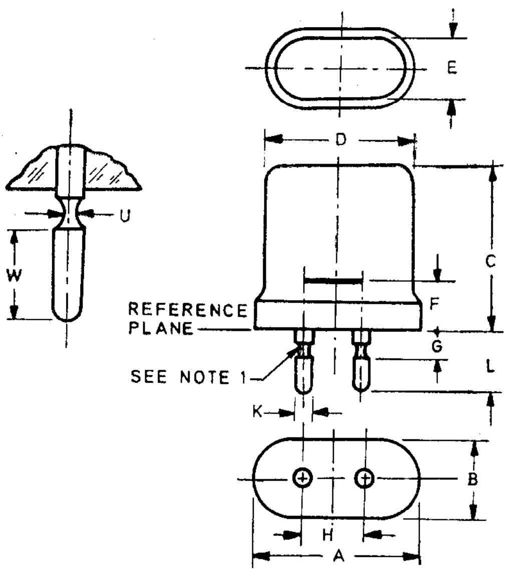


FIG. 12 REFERENCE RESISTORS

Ref	Millimetres		Notes
	Min	Max	
A	—	19·22	—
B	—	8·94	—
C	—	19·68	—
		or	
		38·76	—
D	—	18·41	—
E	—	8·12	—
F	—	5·08	4
G	2·00	—	—
H	12·15	12·54	—
K	1·22	1·32	2
L	5·67	6·29	—
U	0·76	—	1,3
W	4·45	—	—

NOTE 1 — Glass meniscus shall not be in contact with the thin portion of the pin.

NOTE 2 — Pin ends radiused.

NOTE 3 — Shape of undercut at the discretion of the manufacturer.

NOTE 4 — Dimensions *D* and *E* shall be measured above the limit defined by dimension *F*.

NOTE 5 — The millimetre dimensions are derived from the original inch dimensions.

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IS:

1885 (Part V)-1965 Electrotechnical vocabulary: Part V Quartz crystals

1885 (Part XXXIII)-1972 Electrotechnical vocabulary: Part XXXIII Piezo-electric filters

2916 (Part I)-1969 Quartz crystal units used in oscillators: Part I General requirements and tests

2916 (Part II)-1972 Quartz crystal units used in oscillators: Part II Type AA-01

2916 (Part III)-1972 Quartz crystal units used in oscillators: Part III Type AA-02

2916 (Part IV)-1972 Quartz crystal units used in oscillators: Part IV Type AA-03

2916 (Part V)-1972 Quartz crystal units used in oscillators: Part V Type AA-04

2916 (Part VI)-1972 Quartz crystal units used in oscillators: Part VI Type AA-05

2916 (Part VII)-1975 Quartz crystal units used in oscillators: Part VII Type AA-06

2935-1964 Guide for use of quartz oscillator crystals

4570-1968 Crystal holders

5575 (Part I)-1970 Temperature control devices for quartz crystal units (heating type): Part I General requirements and tests

6133 (Part I)-1971 Piezo-electric filter for use in telecommunication and measuring equipment: Part I General requirements and tests

6537-1972 Guide to the use of temperature control devices' or crystal units

7410 (Part I)-1974 Guide to the use of piezo-electric filters: Part I Quartz crystal filters

7410 (Part II)-1975 Guide to the use of piezo-electric filters: Part II Piezo-electric ceramic filters

7957-1976 Basic method for the measurement of resonance frequency and equivalent series resistance of quartz crystal units by zero phase technique in a π-network

7962-1975 Methods of measurement for piezoelectric vibrators operating over the frequency range up to 30 MHz

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